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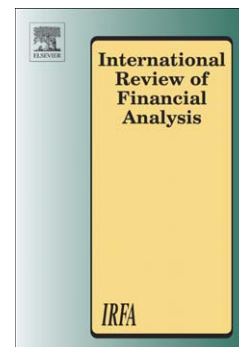
Overnight Interbank Markets and the Determination of the Interbank Rate: A Selective Survey

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Title Page**Overnight Interbank Markets and the Determination of the Interbank Rate: A Selective Survey*****Corresponding author:**

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Abstract

Overnight interbank markets provide critical facilities for the banking system to manage, pool and redistribute its cash reserves. We provide a selective survey of the literature on overnight interbank markets. We outline the typical structure of overnight markets, including the networking relationships involved, as an indispensable prerequisite for a clear understanding of the workings of these markets. We review the theoretical and empirical studies on the determination of the overnight rate, and in that context discuss the implications of the 2007-08 financial crisis. We summarise key issues for further research.

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1. Introduction

In this paper we provide a selective survey of the theoretical and empirical literature on overnight interbank markets. We identify key results and questions arising from the literature, focussing particularly on the theoretical and empirical determinants of the overnight interest rate, and the impact of the 2007-08 financial crisis. To make the literature more accessible to a wider readership than those working directly in the field, we also include an overview of the broad institutional arrangements in overnight markets. The research literature is large, but concentrated on the US Federal funds and the euro zone EONIA¹ (including its predecessors in the euro zone countries); and we therefore focus particularly on these two markets.

Trading in many frontier and emerging markets is relatively thin, and not sufficient to support fully a monetary policy based on open market operations. There is therefore far less research on overnight markets in these countries². There is, however, a considerable volume of research on interbank markets in general, especially following the 2007-08 financial crisis. For example, in a recent survey paper, Summer (2013) explains how network models of interbank exposures allow the mapping of the complex web of financial linkages among many institutions, in order to address issues of system stability and contagion risk. There are also some interesting recent contributions that focus on emerging economies, including work by Martinez-Jaramillo et al. (2014) on Mexico, the development of multi-agent financial network models for India by Markose (2013), work by Vazquez et al. (2012) on Brazil, and the research by León et al. (2015) on Colombia, among others. We depart from these papers by focusing on the overnight interbank market *per se*. Hence, we do not discuss this more general research, except insofar as it is strictly relevant to understanding the overnight markets.

¹ EONIA: *Euro Overnight Index Average*.

² One reason for this is that in many countries overnight interbank market data are not readily available for public use.

The paper is structured to bring out the main contributions of our survey, given that no such survey exists at this time when overnight interbank markets are attracting increasing interest from researchers, policy makers, and practitioners. In section 2 we set out key institutional features of the overnight market focussing on its interaction with central bank reserve requirements and intervention policy. Virtually all overnight lending is unsecured and therefore relationships and networking are particularly important in the functioning of the market. In section 3 we discuss the burgeoning literature on interbank networking insofar as it concerns the overnight market. In section 4 we expound the basic theoretical model of the overnight rate and summarise recent theoretical developments that study market operations in more detail. In sections 5 and 6 we turn to empirical work on the overnight rate. Section 5 reviews the early work, based on the efficient markets approach. There is abundant evidence of apparently predictable movements in overnight interbank rates and in section 6 we examine the explanations which have been advanced for these findings. These focus on the institutional structure of bank reserve management facilities and central bank intervention which tend to produce various level and volatility effects in the overnight rate. Section 7 is concerned with the 2007-08 financial crisis. There is an immense literature on this topic and here too we focus on issues relevant to the overnight market. Specifically, it has been argued that large-scale asset purchases of central banks (“quantitative easing” or QE) and other modifications in operating procedures have fundamentally changed the role of the overnight market, and we focus particularly on this issue. A final section contains some concluding remarks, including the main five messages of the paper.

2. The Institutional Structure of Overnight Interbank Markets

Interbank markets in general enable banks to manage, pool and redistribute their funds, and so provide lending and deposit facilities more efficiently. It was the freeze-up in interbank lending that heralded the onset of the 2007-08 financial crisis (Green, 2011). The overnight market is arguably the most important interbank market. It plays a key role in the monetary and payments

system of a country and provides an essential safety valve for banks. Banks that are short of cash to balance their positions at the end of each day can make up the shortfall by borrowing from the central bank, or in the overnight interbank market, or some combination of the two. Banks with excess cash reserves later in the day have an immediate outlet for these reserves by lending them to other banks in the overnight market. Borrowing from the central bank is usually regarded as “last resort” borrowing as it generally involves a penalty in comparison to borrowing from the market: an above-market interest rate or additional non-interest costs, or both. Therefore, borrowing in the overnight interbank market can be seen as “next-to-last resort” borrowing.

For individual banks, overnight cash shortages or excesses arise either from distributional shocks that temporarily transfer liquidity from one bank to another, or from shocks that affect aggregate liquidity. The overnight market provides banks with liquidity insurance, enabling them to pool liquidity and settle large or unexpected transactions flows resulting from distributional shocks without holding large cash balances for settlement purposes. Aggregate shocks can only be insured by the central bank increasing or decreasing the aggregate supply of liquidity (reserves). In managing the aggregate supply of reserves, central banks face a difficult set of conflicts. Bank reserves are required to finance the payments mechanism but are also used to underpin monetary policy. The funds required for payment purposes typically far exceed the quantity consistent with the central bank’s desired interest rate. Central banks must allow a high level of reserves for payments purposes during each day, but shrink them back to a level consistent with monetary policy objectives at the end of the day. The element of liquidity insurance implicit in reserve management operations may create moral hazard, and lead to excessive risk-taking by banks.

The interest rate in the overnight market serves several important purposes. First, it is often used as the main operational target for monetary policy: the Federal funds rate in the US and the

unsecured call rate in Japan³. Alternatively, it may act as a key short-term indicator, as does the EONIA for The European Central Bank (ECB) and the SONIA for the Bank of England (BoE)⁴. Pressures on the financial system are reflected rapidly in a shortage or excess of bank reserves and corresponding movements in the overnight rate. Second, as it is the shortest maturity interest rate in the financial system it acts as the anchor for the term structure of interest rates. Movements in the overnight rate are often followed by changes in longer-term rates. Third, the overnight rate is the first link in the transmission mechanism of monetary policy. Policy actions have their first effects in the overnight market, and these spread through the financial system and the whole economy. Understanding the overnight interbank rate is therefore of crucial importance for the implementation of monetary policy.

To balance transactions and policy consideration while ensuring an orderly overnight market, central banks typically adhere to a highly structured pattern of activities during the working day linked to the operation of the real-time gross settlement system. See Akhtar (1997) on the US Federal Reserve (the Fed); Bank of England (2012, 2014); Bank of Japan (2012); Hartmann, Manna and Manzanares (2001) and European Central Bank (2011). Links between the overnight market and the market for bank reserves are determined mainly by reserve requirement arrangements (Gray, 2011). The amount of reserves a bank is required to hold is calculated as a given percentage (*the reserve requirement ratio*) of selected (eligible) deposit liabilities in a particular time period: *the calculation period*. The calculation period may be a single day (Turkey), or the average of eligible liabilities over a period such as a fortnight (US) or a month (Japan) preceding that in which the reserves must be held. The holding period for required reserves is called *the maintenance period*. This may be daily (Kenya until 2011⁵); more usually it is between 14 days (US) and one month (Japan), and gives a regular fixed period within which

³ From March 2001 the call rate was replaced by a quantitative target for commercial bank reserve balances at the Bank of Japan. See the discussion in section 7.

⁴ SONIA (sterling overnight index average) refers to the rate on unsecured loans and RONIA (repo overnight index average) refers to that on secured loans (Bank of England, 2012).

⁵ Central Bank of Kenya, 2011.

banks have to meet their reserve requirements⁶ (O'Brien, 2007). Unless the reserve test has to be met on a daily basis, a *reserve averaging* procedure is used. This means that commercial banks must meet the reserve test on the final day of the maintenance period (*the settlement day*) based on the average of reserves over the maintenance period⁷. Thus, banks know for certain their required minimum reserves only on the settlement day. Reserve averaging serves an important practical purpose: in permitting some volatility in the quantity of required reserves over the maintenance period, it helps prevent excessive volatility in overnight interest rates and central bank intervention rates (Gray, 2011).

The main day-to-day determinants of banks' reserve demands are the transactions flows through the banking system. Some of these are highly predictable and largely distributive and temporary in nature, such as the monthly cycle of wage and salary payments. Other flows are random shocks which may be aggregative or distributive, permanent or temporary, or some combination. Under a reserve averaging system banks can have a shortage or excess of reserves during the maintenance period provided the average is satisfied by the end of the period. This enables banks to manage the predictable component of transactions flows without excessive recourse to the interbank market or the central bank on a day-to-day basis, and so helps to dampen daily and intra-day fluctuations in the overnight rate. Reserve averaging enables the central bank to delegate to commercial banks much of the process of reserve management in the face of stochastic shocks; and intervention to inject or drain reserves can be carried out smoothly over the maintenance period (Gray, 2011). The regular cycles of reserve calculation and maintenance imply that the demand for reserves will vary systematically over the maintenance period. However, these predictable variations in reserve demand should not necessarily create predictable patterns in the overnight rate. In principle, banks should be able to eliminate any

⁶ The maintenance period in the Eurozone was increased from 4 to 6 weeks effective January 2015 to coincide with the contemporaneous increase in the interval between successive meetings of the governing council.

⁷ In the US, the weekend accounting convention dictates that Friday's data count three times in the averaging.

predictable patterns through arbitrage during the maintenance period (Hamilton, 1996). We discuss this point in sections 5 and 6.

The classical interpretation of the relationship between central bank and overnight interest rates is traditionally ascribed to Bagehot. “Bagehot’s rule” was that “...in time of panic it [the Bank of England] must advance freely and vigorously to the public out of the reserve. [but] ... these loans should only be made at a very high rate of interest ... [and] these advances should be made on all good banking securities ... ” (Bagehot 1873, 187-88, cited by Grossman and Rockoff, 2015). If banks are short of reserves and unable to replenish them in the overnight market they should be able to borrow from the central bank but with high-grade security and at a penalty rate in comparison with market interest rates. Bagehot was concerned with times of crisis. In normal times the doctrine was generally interpreted to mean that the central bank discount rate should be above the overnight rate. This was consistent with the historic operating procedures of some central banks but not all. The Fed’s discount rate was invariably below the key Federal funds rate from the 1960s until the change in operating procedures in January 2003 (Cecchetti, 2009).

More recently, several central banks have followed the ECB and offered an interest rate “corridor” (European Central Bank, 2011). This is now the normal *modus operandi* of the BoE (Bank of England, 2012); and the *de facto* operating procedure of the Fed since it began paying interest on reserves in October 2008 (Kahn, 2010). The ECB provides two standing facilities for banks (in addition to discount window borrowing) in the form of marginal deposit and lending facilities at fixed rates. The deposit and lending rates form a corridor within which the key intervention rates normally lie. Until the 2007-08 financial crisis, the width of the corridor was 200 basis points. It was reduced successively after the financial crisis, as the ECB resisted the introduction of a negative deposit rate. A negative deposit rate was introduced in June 2014, and at this time the corridor was 50 basis points wide. Other central banks operate with corridors of different widths. The main refinancing operations (MROs) of the ECB are carried out at a fixed rate and a variable rate at which banks tender for repurchase agreements (repos) supplied by the

ECB. The main overnight interbank rate (EONIA) generally lies in the corridor set by the standing facilities, but the variable MRO rate sometimes strays outside (Välimäki, 2003).

The overnight market is also influenced by central bank intervention policies. From the early 1980's European central banks increasingly used repos to provide assistance to banks (Kneeshaw and van den Bergh, 1989). In normal times, The ECB and other central banks now rely exclusively on repos in open market operations (Bindseil, 2004), although the large-scale outright asset purchases that followed the financial crisis marked a departure from this strategy, and a return to older policy methods. Repo operations are the normal intervention method of choice, as they provide greater flexibility, effectiveness and efficiency for money market management, as compared with traditional instruments such as asset purchases and discount window borrowing. First, in a repo auction the central bank determines the maturity of the repo, the date of refinancing and the volume of reserves banks can borrow. Second, repos allow a fine-tuning of banks' refinancing conditions (and thus of money market rates), since they mature and are renewed at relatively short intervals. Announcements of repo operations constitute one of the main indicators of central bank intentions in many countries. For commercial banks, borrowing reserves in the interbank market is an obvious alternative to central bank credit, but these transactions only redistribute central bank money within the banking sector. When the central bank restricts the supply of bank reserves in a repo auction, the resulting excess demand for central bank money pushes the overnight rate higher. Hence banks have to borrow their missing reserves at a penalty rate: either at the policy rate or in the money market at a higher rate than before the central bank's intervention (Bindseil, 2004).

3. Relationships and Networking in Overnight Markets

The important feature of the overnight interbank market that distinguishes it from markets in longer-term loans, and borrowing from the central bank, is that the lending is all unsecured

(European Central Bank, 2011; Bank of Japan, 2012; US Federal Reserve Board, 2005)⁸. Banks utilise lines of credit with other banks for borrowing and lending, and lenders must determine the credit-worthiness of the borrowers to whom they lend. This means that relationship and network effects are important in these markets. Relationship banking implies that institutions with lesser reputations will tend to transact regularly with a consistent and relatively limited number of counterparties with whom they have an established relationship. This mitigates asymmetric information and may be expected to yield finer rates for participating banks (Furfine, 1999, 2000). Larger banks may be expected to transact more widely. The largest banks may form a core group, transacting extensively with one another and with the smaller banks in the system (Imakubo and Soejima, 2010). In their study of Portugal, Cocco, Gomes and Martins (2009) find that banks that have a higher proportion of non-performing loans and therefore greater liquidity risk depend more heavily for liquidity insurance on banks with whom they have an established long-term relationship. They also find that interbank relationships are more persistent among domestic banks than between domestic and foreign banks. Affinito (2012) also finds that banking relationships are more durable between Italian banks than as between Italian and foreign banks.

Networking relationships in interbank markets create interdependencies with a potential for contagion, especially where, as in the overnight market, there is an absence of collateral: a liquidity or solvency problem in one bank can easily spread from one bank to another, channelled through the interbank network and triggering multiple bank failures (Freixas, Parigi and Rochet, 2000; Iori, Jafarey and Padilla, 2006; Nier, Yang, Yorulmazer and Lentorn, 2007). This issue of systemic risk was brought to the fore by the 2007-08 financial crisis in which initial problems at certain banks triggered potentially catastrophic losses to the whole financial system (Glasserman and Young, 2015). Following the seminal contribution of Boss, Elsinger, Summer and Thurner (2004), network theory has been used to characterise the linkages in financial

⁸ Exceptionally, in the UK, there are active markets in secured and unsecured overnight loans. See footnote 4.

systems and identify possible sources of contagion and systemic risk. In this approach each bank is viewed as a node in a network which is linked to other nodes (banks) by the banking relationships represented by the value and terms of borrowing and lending transactions. A complete interbank market structure may be defined as one in which every bank has a bilateral relationship (lending and borrowing) with every other bank. An incomplete structure is one in which banks have relationships with a limited number of other banks. Early research suggested that a complete structure is inherently less vulnerable to contagion than one which is incomplete, especially if an incomplete structure involves a series of one-way relationships (borrowing or lending) effectively forming a one-way “chain of contagion” (Allen and Gale, 2000).

Early research on interbank networks focussed on network topology; that is, the linkages among banks, instead of on the characteristics of the banks themselves. Craig and von Peter (2014) argue that banking networks do not arise randomly as a result of outside forces but emerge endogenously because of the nature of individual banks, especially differences in size and reputation that tend to produce networks in which relationships are tiered in a “core-periphery” structure, with a limited number of money centre banks transacting with each other and with smaller banks; meanwhile, smaller banks transact mainly with a relatively few large banks. Interbank networks are relatively concentrated, with a high proportion of transactions by number and size being placed by a relatively small number of banks, such as in the Federal funds market (Furfine, 1999) and the Japanese call market (Imakubo and Soejima, 2010).

Even so, there remains disagreement in theory and in practise about the optimal structure of a financial network, especially in being robust in the face of shocks such as the 2007-08 financial crisis. The argument that a complete structure is more robust than one which is incomplete (Allen and Gale, 2000), depends in part on the magnitude of the shocks to which the system is subject as well as the characteristics of the banks at each node and their lending and borrowing relationships. If a negative shock is sufficiently large, financial systems which are less strongly interconnected may be less vulnerable to collapse because larger institutions can act as a buffer

against the propagation of the shock to smaller or weaker institutions (Acemoglu, Ozdaglar and Tahbaz-Salehi, 2015). Networks that have a core-periphery structure tend to be more robust the stronger are the core banks, but also the more similar in size and structure are these banks, as they provide a collective defence against systemic risk (Glasserman and Young, 2015). In general therefore, systems which are overly complex and “too interconnected” may be more vulnerable to collapse (Gai, Haldane and Kapadia, 2011).

In terms of the empirical evidence, Fricke and Lux (2015) identify that Italian banks are formed into a core-periphery structure that has been relatively persistent over time and as among banks. The interbank network is relatively incomplete with core banks trading with each other and with at least one non-core bank, but sometimes no more than one. They conjecture that core banks have a comparative advantage in gathering and distributing information, because of economies of scale in information processing. Parallel results are obtained by Affinito (2012) who investigates the persistence of banking relationships in Italy during the 2007-08 financial crisis. He also finds that the relationships between lending and borrowing banks remained durable through the financial crisis even as borrowing banks experienced temporary liquidity problems. A less intuitive structure is identified in Kenya’s interbank market (Oduor, Sichei, Tiriongo and Shimba, 2014), where the strongest network relationships are those among smaller banks and much less as between large and small banks.

Studies of the UK by Wells (2004), of the Netherlands by Lelyveld and Liedorp (2006), and of Italy by Mistrulli (2011) broadly confirm that risk of systemic failure depends on the exact structure of the interbank network. A single bank failure is rarely sufficient to trigger the failure of other banks, but it can weaken substantially the capital holdings of the banking system. The severity of contagion depends on the linkages in the interbank market (Wells, 2004), and on the size and centrality of the initial failing bank (Lelyveld and Liedorp, 2006): the larger and more central the initial failure, the more likely it is that there will be contagion. Evidence from Mexico confirms that financial fragility also depends on the characteristics of individual banks as

well as the network itself. The system becomes more fragile when: there are more overexposed banks; there are more paths in the network going through overexposed banks; and negative shocks fall more heavily on “core” banks (Martinez-Jaramillo, Perez Perez, Avila Embriz and Lopez Gallo Dey, 2010).

However in Switzerland, Sheldon and Maurer (2004) found that although the probability of a single bank failure was relatively high, the risk of it contaminating the whole system through the interbank market was much lower. A similar study of German banks by Upper and Worms (2004) also argued that the probability of contagion was relatively low but identified smaller banks as being the most vulnerable to failure, although the mechanism for contagion works through the larger banks. In contrast, Muller (2006) uses graph theory to describe a “hub and spoke” structure in the Swiss interbank market where the two major banks are involved in a high proportion of all the transactions with other institutions. She identifies systemically important banks using 5 key characteristics: they have exposures and liabilities to many other banks; they have large interbank exposures; their failure would weaken numerous banks; their counterparties are also important banks; and they lie on numerous potential paths for contagion (Muller, 2006). On this basis Muller argued that the Swiss banking system was very vulnerable to contagion because of the centrality of the two main banks. A similar structure is reported for Colombia by León, Machado and Murcia (2014). They investigate linkages across the whole financial system including banks and non-banks. They find that banks are systemically more important than non-banks and, like Switzerland, just two banks stand at the apex of the money market, rendering it potentially vulnerable to contagion in a similar way. Mistrulli (2011) argues that the maximum entropy approach used by these authors tends to overstate the risks of contagion in incomplete networks. In a study of Italy he finds that there are several buffers limiting contagion, especially if bank holding companies are allowed to recapitalise failing affiliates in a crisis. In these circumstances, it would seem that size does matter.

Networking in the interbank market is not only pivotal for liquidity management it can also provide monitoring tools that could counterbalance some of the risks of contagion. Rochet and Tirole (1996) argue that interbank relationships provide incentives for banks to monitor each other. If lending banks believe that they are exposed to potential losses on unsecured loans, they will monitor borrowing banks, and we would expect banks to be particularly good at identifying the risk of other banks. This is a form of market discipline that could supplement formal bank regulation and supervision. Banks who participate in the interbank market must have a high degree of transparency and disclosure, to transmit information and reduce uncertainty for lenders and borrowers. They may also maintain a higher level of reserves than non-participants so as to reduce liquidity risks. In the Federal funds market, Furfine (2001b) found that banks with higher profitability, fewer problem loans and higher capital ratios do indeed pay lower interest rates for borrowing. Likewise, more risky banks tend to borrow less than others (King, 2008). Comparable results are obtained for German banks in a dataset that includes the run-up to and aftermath of the 2007-08 financial crisis (Bräuning and Fecht, 2012). However, Dinger and Von Hagen (2009) argue that these studies only screen borrowing banks' prior risk before the loan rather than lending banks' monitoring after the loan. They suggest that the weak evidence of market discipline may be attributable to a focus on highly developed banking markets, where interbank exposures can be quickly abandoned by both counterparties. Using data on smaller banks in Central and Eastern European countries, they find that banks with greater long-term exposure to the interbank markets are those with lower risks in their loan portfolios.

4. Theories of Reserve Management

We now consider theories of reserve management and the determination of the overnight interest rate. Theory largely focusses on a single market interest rate, although on any given day, there are many overnight rates, corresponding to loans made at different times in the day. In empirical time-series work, the daily interbank rate is usually calculated as a single value-weighted average of rates on every transaction on that day. This minimises the impact of intraday variations in market liquidity. Several papers do consider the relationships between the time series and cross-sectional pattern of rates, and we refer to these as necessary.

The basic theory of the overnight market utilises the stochastic reserve management model of Poole (1968) and Baltensperger (1972, 1980)⁹. We summarise this model before considering more recent developments. The model considers the process by which an individual bank manages stochastic net flows of deposits associated with the daily clearing. It decides each day how much to lend to its customers before it knows the outcome of the deposit flows. If the net inflow of deposits exceeds lending, the bank accumulates excess reserves and suffers a penalty because the return on reserves is less than the return on loans. If deposit inflows are too low, the bank borrows from the central bank, and incurs a penalty: first, because the cost of discount window borrowing may be higher than the market rate and second, because there may be non-interest costs of discount window borrowing. Since the net flows at clearing are not known until the end of the day, a bank will invariably find itself with excess or deficient cash at this time. There is also a range of issues associated with reserve requirements as discussed in section 2. Here we assume that the reserve test must be met daily; and the level of required reserves is set to zero without loss of generality. In this model there is no interbank market; we introduce it explicitly below. Thus we define:

a = the day's flow of loans; with $a > 0$

⁹

An alternative is the state-preference liquidity trading model of Allen and Gale (2004).

e = flow of cash; with $e \geq 0$

c = borrowing from the central bank; with $c \geq 0$

r_a = the return on loans

r_e = the return on reserves (initially we assume $r_e = 0$)

i_c = the interest cost of borrowing from the central bank (discount rate)

γ = the non-interest (pecuniary or non-pecuniary) cost of borrowing from the central bank

which we assume to be a fixed penalty irrespective of the amount borrowed.

The net flow of deposits is governed by a random variable: b ($b \geq 0$):

$\varphi(b)$ refers to the probability distribution governing deposit flows, and:

$\Phi(\lambda) = \int_{-\infty}^{\lambda} \varphi(b) db$ is the cumulative probability that $b < \lambda$.

The cost of deposits is assumed to be negligible.

The bank's daily sources-uses statement is given by:

$$a + e = b + c$$

...(1)

Banks are risk-neutral with expected profits on any particular day given by:

$$E\Pi = r_a a - i_c \int_{-\infty}^a (a-b)\varphi(b)db - \gamma \int_{-\infty}^a \varphi(b)db$$

...(2)

The first term in (2) is loan revenue decided by the bank given the loan rate. If $b > a$, excess reserves are $e = b - a$, and earn no interest. If $b < a$, the bank must borrow $c = a - b$ at an

interest cost of i_c per £ and a fixed cost $= \gamma$ for a loan of any size. A convenient normalisation is to scale the fixed cost to the exogenous central bank interest rate (i_c).

Differentiating (2) with respect to a gives:

$$\frac{\partial E}{\partial a} = r_a - i_c \Phi(a) - \gamma i_c \varphi(a) = 0$$

...(3)

or: $r_a / i_c = \Phi(a) + \gamma \varphi(a)$

...(4a)

In the special case where $\gamma = 0$, we have:

$$r_a / i_c = \Phi(a) < 1$$

...(4b)

Without a fixed penalty ($\gamma = 0$), we get the well-known result (4b), due to Poole (1968): the probability of having to borrow from the central bank is set equal to the ratio of the average lending rate to the average borrowing rate (the central bank discount rate). This implies that the central bank discount rate must exceed a bank's average lending rate, and is likely to do so by a considerable margin (Clouse and Dow, 1999). If the discount rate were not a penalty rate, banks would have an incentive to borrow unlimited amounts from the central bank.

If there are non-interest costs of borrowing from the central bank ($\gamma \neq 0$), the discount rate can be below market rates. Non-interest costs may be divided into three. First, borrowing from the central bank is less flexible than borrowing from the market: the period of the loan is set by the central bank. Second, borrowing from the central bank is secured, and collateralisation is itself

costly. Third, there may be a “stigma” of borrowing from the central bank which discourages banks from borrowing as frequently or as much as they wish (Furfine, 2001a).

Non-interest costs may include variable and fixed elements. Clouse and Dow (1999) pointed out that the existence of fixed costs of borrowing from the central bank is sufficient to produce a more realistic (smaller) differential between i_c and r_a , depending *inter alia* on i_c and γ (4a)¹⁰. The discount window is more costly for smaller banks than for larger banks because smaller banks cannot spread the fixed costs over such a large loan as can bigger banks. This suggests that larger banks will self-select to be regular borrowers from the central bank to benefit from the economies of scale. This frees up the cash supplied by the central bank for smaller banks to hold positive excess reserves, avoiding recourse to the discount window. This argument offers an explanation for a smaller penalty ($i_c - r_a$) and the common observation that the predominant users of the discount window are larger banks. It is also consistent with the general pattern of interbank market transactions in which smaller banks tend to lend excess reserves to larger banks: in the US (Allen, Peristiani and Saunders, 1989), Italy (Affinito, 2012) and elsewhere. A further argument, put forward in the euro zone, is that certain banks have a comparative advantage in collateralising debt, because they have higher-quality liquid assets and lower costs of collateralisation. These banks borrow from the central bank and lend to other banks with higher collateralisation costs (Neyer and Wiemers, 2004).

To study the interbank market and a central bank interest rate corridor, the basic model is usually amended by assuming that banks borrow or lend deterministically in the interbank market and then, following revelation of deposit flows, either lend to or borrow from central bank standing facilities at a penalty rate in either direction. To focus on the corridor, we set loans (a) to zero, and introduce borrowing and lending in the interbank market as:

¹⁰ From (4a), $i_c > r_a$ if $1 > \Phi(a) + \gamma i_c \phi(a) > \Phi(a)$; which is true if: $1 - \Phi(a) > \gamma i_c \phi(a) > 0$. The right-hand inequality is true; and the left-hand inequality holds for plausible values of i_c , normalising γ at unity.

h = interbank lending; with $h \geq 0$;

m = interbank borrowing; with $m \geq 0$

and: r_h = the return on interbank loans; i_m = the cost of interbank borrowing

In equilibrium $r_h = i_m$. However, the usual development of this model (Välimäki, 2003) begins with an individual bank which exogenously decides to lend (for example) in the interbank market, discovers its deposit flows and then uses the standing facility. If $h < b$, the bank is a depositor with the central bank ($e + h = b$); if $h > b$, the bank borrows from the standing facility ($h = b + c$). The day's expected profit of any lending bank is given by:

$$E\Pi = r_h h + r_e \int_h^\infty (b-h)\varphi(b)db - i_c \int_{-\infty}^h (h-b)\varphi(b)db - \gamma_c \int_{-\infty}^h \varphi(b)db \quad \dots(5)$$

So:
$$\frac{\partial E}{\partial h} = r_h - r_e (1 - \Phi(h)) - i_c \Phi(h) - \gamma_c \varphi(h) = 0 \quad \dots(6)$$

and:
$$r_h = \Phi(h)i_c + (1 - \Phi(h))r_e + \gamma_c \varphi(h)$$

or:
$$\Phi(h) = \left(\frac{r_h - r_e}{i_c - r_e} \right) - \left(\frac{\gamma_c \varphi(h) i_c}{i_c - r_e} \right) \quad \dots(7)$$

...(8)

$\Phi(h)$ is the probability that the bank must borrow from the standing facility ($b < h$). Therefore:

$$h = \Phi^{-1} \left\{ \left(\frac{r_h - r_e}{i_c - r_e} \right) - \left(\frac{\gamma \varphi(h) i_c}{i_c - r_e} \right) \right\}$$

...(9)

is the supply of interbank loans. The lower the interbank rate the less is the supply of loans.

If $\gamma = 0$, (7) states that the interbank (lending) rate is an average of the rates on the two standing facilities and lies within the interest rate corridor. This is not an equilibrium as it refers only to banks who are lending in the interbank market. Other banks exogenously decide to borrow. Their optimisation problem determines the demand for interbank loans (m : $m > 0$; $h = 0$) in a similar form to (9). For these banks, the lower the interbank rate, the greater is their demand for loans. The equilibrium interbank rate is found by setting $h = m$ and $r_h = r_m$. A closed-form solution is available only for specific probability distributions which we do not pursue here¹¹. Where there are fixed costs of borrowing from the standing facility ($\gamma \neq 0$), the supply of loans in the interbank market is reduced as this reduces the risk of borrowing from the standing facility. However, the demand for interbank loans increases, to reduce the probability of borrowing from the central bank. Thus, a higher fixed penalty tends to increase the equilibrium interbank rate, relative to the discount rate. The relationship between the interbank rate and the corridor ($i_c - r_e$) depends on interest and non-interest costs. However, it is clear from (8) that the narrower is the corridor the higher is the probability of utilising the standing facility. In general, Bindseil and Jablecki (2011) show that a narrower corridor will be associated with: greater commercial bank

¹¹ See Neyer and Wiemers (2004) for an example with the uniform distribution.

recourse to the central bank, less use of the overnight market and less interest rate volatility within the corridor.

The basic model has been extended in many ways, notably to incorporate greater institutional detail about the interbank market and central bank policy, especially the maintenance period (Perez Quiros and Rodriguez Mendizabal, 2006) and repo auctions (Ayuso and Repullo, 2003; Välimäki, 2003). A key issue is to understand what determines the allocation of banks' transactions between the interbank market and the central bank. If banks are risk-neutral¹², diversification can only occur if the different sources of borrowing and lending are subject to increasing costs. Otherwise, the overnight rate would converge to the discount rate, as banks transacted exclusively in the lowest-cost market (Bucher, Hauck and Neyer, 2014). Therefore, to understand why banks may limit their transactions with the interbank market or the central bank we need to consider the relative costs of operating in the different markets.

Neyer and Wiemers (2004) argue that banks do face increasing (interest and non-interest) costs in the interbank market. Consider first borrowing in the interbank market. Since this is unsecured, it typically involves the use of lines of credit. If a bank has to borrow more, it will incur transactions and search costs if it uses more different lines of credit. Splitting larger transactions into smaller ones to utilise existing lines of credit is also likely to prove costly (Bucher *et. al.*, 2014). Alternatively, it will face congestion costs if it uses fewer lines of credit, as it is likely to encounter increasing borrowing costs (Neyer, 2004). Larger borrowers may incur increased asset monitoring or recall costs, such as early sales of bills on the following day. Some banks may limit their exposure to interbank trading for capital adequacy reasons (Välimäki, 2006). Linzert and Schmidt (2011) argue that banks may be less willing to lend money in unsecured interbank trading at times of greater aggregate uncertainty.

¹² This is a standard assumption. An exception is Ho and Saunders (1985) who assume risk-averse banks.

Banks are also likely to face increasing costs of borrowing from the central bank. First, discount window borrowing is secured and therefore involves a collateralisation cost. Collateralisation ties up liquid assets that could have been available for outright sale and may constrain the asset choices of banks who believe they may have to be discount window borrowers later in the day (Neyer, 2004). Collateralisation costs are likely to include a fixed and a variable element, especially because the form of acceptable collateral will vary across lenders (Välimäki, 2006). Second are the costs of participation in the central bank repo auction. A common format is the fixed-liquidity, variable-price auction: banks that want to borrow more face increasing costs otherwise they may be outbid in the auction (Wurtz, 2003; Nautz and Offermanns, 2007). Third, borrowing from (and lending to) the central bank, whether through the discount window or repos is typically for a fixed period.

Lenders face symmetric costs to borrowers: transaction, search, congestion and monitoring costs of lending larger amounts and to more different borrowers. Although lenders may charge higher interest rates to large borrowers they may also face a higher risk of default or rollover. There are similar costs on the lending side of the central bank repo market. A fixed-liquidity, flexible-price auction of reverse repos will only mop up the liquidity of a bank if it bids high enough (lower interest rate) to maximise its chance of success, and the larger its excess liquidity, the higher must be its bid *ceteris paribus*.

Incorporating these factors into a more comprehensive model of the interbank market yields several conclusions regarding the determinants of the overnight rate¹³. First, the overnight rate will adjust as central bank rates are changed by the authorities, although the adjustment is not necessarily one-for-one. The rate will not always lie within the central bank's interest rate corridor, but may be above the borrowing rate. This depends on the relationship between the full costs of borrowing in the interbank market as against those of borrowing from the central bank.

¹³ The following discussion summarises results established, *inter alia*, in: Neyer and Wiemers (2004); Välimäki (2003); and Afonso and Lagos (2015).

Second therefore, costs of operating in interbank and other markets directly affect both the average level of the interbank rate and the daily cross-sectional distribution of rates. Third, other central bank operating tools such as the structure and size of the repo auction and reserve requirements will affect the interbank rate. Fourth, aggregate and distributional liquidity shocks affect the level and distribution of rates. An aggregate (negative) liquidity shock tends to raise the interbank rate, and increase its volatility, and may also increase market volume. The effects of distributional shocks are less clear. An increase in the cross-sectional dispersion of deposit flows tends to increase the rate interbank lenders will demand but reduce the rate that borrowers will pay. Lenders demand a higher rate because increased dispersion increases the quantity risk of lending, and therefore the price risk because of increasing costs. Since the quantity and price risk of borrowing are also higher borrowers would prefer a lower rate. The impact on the interbank rate depends on the relative strength of these two effects and cannot necessarily be determined *a priori*.

In theory therefore, the overnight interbank rate is determined by a range of factors including: other interest rates, the costs for banks of operating in the market, central bank operations and discount policy, and shocks to bank liquidity which must be settled by the close of business. Many of these factors are determined partly by the institutional framework, including the interbank network and relationships. Overall though, we would expect to find strong linkages between the interbank rate and other short-term interest rates, especially the central bank's rates which are the immediate alternative sources of overnight cash for a commercial bank.

5. Empirical Studies: The Martingale Hypothesis and Monetary Policy

The modern empirical literature on the overnight rate was initiated by Shiller, Campbell and Schoenholtz (1983) and Hamilton (1996), who tested the martingale hypothesis for the US Federal funds rate. Demand for reserves varies systematically over time because of the regular cycles of reserve computation and maintenance. If banks face an average reserve requirement,

reserves on any one day are perfect substitutes for reserves on any other day within the maintenance period. Therefore, predictable variations in reserve demand should not create predictable patterns in the (overnight) Federal funds rate within each maintenance period. Banks can arbitrage away expected differences between the current and future cost of funds by selling reserves on “high” rate days and buying them on “low” rate days, while still meeting the reserve requirements on settlement day. This argument does not apply to the settlement day itself since reserves are not perfect substitutes across maintenance periods.

Shiller *et al* (1983) found that the Federal funds rate did not follow a martingale. Hamilton (1996) proposed a more complete empirical model of the daily funds rate, simultaneously modelling the conditional mean and variance using a regime-switching EGARCH model:

$$i_t = i_{t-1} + \beta'X_t + \varepsilon_t$$

...(10)

$$\frac{\varepsilon_{t-j}}{\sqrt{h_{t-j}}} \sim pN(0,1) + (1-p)N(0, \sigma^2)$$

...(11)

$$\ln(h_t) = \lambda'V_t + \sum_{j=1}^n \left[\delta_{j,1}(\ln(h_{t-j}) - \lambda'V_{t-j}) + \delta_{j,2} \frac{\varepsilon_{t-j}}{\sqrt{h_{t-j}}} + \delta_{j,3} \left(\frac{|\varepsilon_{t-j}|}{\sqrt{h_{t-j}}} - E \frac{|\varepsilon_{t-j}|}{\sqrt{h_{t-j}}} \right) \right]$$

...(12)

Here, i_t is the Federal funds rate, with conditional mean given by (10); and X_t is a vector of dummy variables for calendar and end-of-reserve-period effects which may affect martingale

behaviour. The error process (ε_t) is a mixture of normal distributions (11) to control for the occurrence of irregular outliers. The EGARCH process (12) is used to model the observed persistence in the conditional variance; V_t is a vector of dummies. Hamilton (1996) concluded like Shiller *et al.* (1983) that the daily Federal funds rate did not follow a martingale even within the maintenance period. He found a strong predictable pattern of day-of-the-week and other calendar effects¹⁴, including predictable market tightening on settlement days when overnight rates tended to be systematically higher than at other times in the maintenance period.

In a study of the G7 and euro zone countries, Prati, Bartolini and Bertola (2003) investigated the robustness of these findings using a similar EGARCH model to represent the systematic time-variation in the variance which is characteristic of overnight market rates in general. Following Hamilton (1996), the conditional mean and variance are explained by (predictable) dummy variables. They verified the non-martingale property of the overnight rate, but found that its behaviour varied considerably across countries. Market tightness on settlement days appeared to be peculiar to the US and was not evident in other G7 countries (except Germany). However, higher overnight rate volatility on settlement days was a common feature of the G7, but more detailed comparisons suggested that the time series patterns of the conditional mean and variance of the overnight rate were closely related to specific features of each country's central bank operating and intervention procedures in the market for reserves.

Perez Quiros and Rodriguez Mendizabal (2006) also used an EGARCH model to test the martingale hypothesis for German and European overnight rates, with results that are broadly consistent with Prati, *et al.* (2003). There were strong daily effects in the overnight rate in Germany prior to European Monetary Union (EMU), quite similar to those in the Federal funds rate, but many of these effects appear weaker or different in nature following EMU¹⁵. The authors speculate that this may be due to the changes in monetary arrangements after EMU, and

¹⁴ These included pre- and post-holiday, end-quarter and end-year effects.

¹⁵ After EMU, the variable to be explained is the EONIA rate, except that on the first day of each reserve maintenance period the EONIA is replaced by the spread between EONIA and the rate on the MROs.

to differences between US and European arrangements: a longer maintenance period in the euro zone, and the existence of standing deposit and lending facilities. Perez Quiros and Rodriguez Mendizabal (2006) argue that there are good reasons why bank reserves in the euro zone are not perfect inter-temporal substitutes within the maintenance period, even if banks expect rates to be constant. This is because of the asymmetry between reserves and borrowings. As a bank accumulates reserves in any maintenance period, this increases the likelihood that it will find itself with excess reserves. Once a bank has accumulated its required reserves, it is effectively locked-in to this state as reserve holdings are strictly non-negative. Therefore banks will prefer to be short of reserves in the early part of the maintenance period, and this creates a profile of increasing demand for reserves as the period progresses. This implies a systematic upward trend in the overnight rate as settlement day approaches and banks seek reserves. They also argue that deviations from a martingale will be reduced as the width of the central bank's interest rate corridor decreases. Perez Quiros and Rodriguez Mendizabal (2006) show that overnight rates in Germany did tend to rise towards the end of the maintenance period, but following EMU, EONIA rates tended to decline as settlement day approached. They attribute the change, in part, to the introduction of the standing deposit facility following EMU. However, Fecht, Nyborg and Rocholl (2008) argue that higher rates at the beginning of the maintenance period may be driven by a temporary shortage of liquidity at this time. Indeed, there is evidence that the ECB tended to over-allot reserves towards the end of the maintenance period (Nautz and Offermanns, 2007).

If the overnight rate is not a martingale, it could be because of anticipations of or reactions to central bank policy decisions. In the euro zone, the interest rate on the ECB's MROs and the overnight rate both play pivotal roles in ECB operations aimed at steering interest rates. As the ECB does not have an official operating target for any interbank rate, the MROs ensure equilibrium by satisfying demands for central bank balances in a smooth fashion over the course of each maintenance period (Manna, Pill and Quiros, 2001). In the absence of liquidity shocks or new information, market expectations about the ECB's interest rates should be reflected in

overnight rates at the beginning of the maintenance period. Expectations about overnight rates within the period should affect spot overnight rates from the beginning of the maintenance period. If the market can forecast ECB moves then the behaviour of overnight rates within the maintenance period should not be significantly affected by monetary policy announcements following ECB Governing Council meetings. Gaspar, Perez-Quiros and Sicilia (2001) looked at whether ECB interest rate announcements influenced the stochastic behaviour of overnight rates using the regime-switching EGARCH model of Hamilton (1996) and Perez Quiros *et al.* (2006)¹⁶; and found that the announcements did not affect either the level or variability of overnight money market interest rates.

Subsequent literature has built on this framework, using GARCH-class models to analyse the volatility of overnight rates. Empirical research has focussed on the reserve maintenance period, central bank operations, as well as the impact of liquidity and payments shocks.

6. Reserves Management and Central Bank Operations

The foregoing arguments suggest that, with reserve averaging, the reserve management process may create predictable variations in the interbank rate. Bank reserves management is closely related to the settlement system, since reserves are required to meet the daily payment needs of banks' customers. Furfine (2000) developed and tested a model of US bank reserve management and the Federal funds market that explicitly incorporates interbank payments and settlement. The model does not rely on the transactions costs and market frictions that are central to Hamilton's (1996) explanation for the predictable pattern of overnight rates. Instead, it is built on the assumption that each bank cannot know for certain its final reserve balance before transacting in the funds market. Furfine (2000) argues that the predictable pattern in the overnight rate is associated with the lack of a deep funds market late in the day. Banks face

¹⁶ The issue of how well markets can anticipate the Fed's monetary policy moves has been investigated using Fed funds futures prices (Krueger and Kuttner, 1996).

uncertainty about their end-of-day reserves which is increasing in the volume of their payment obligations. Banks cannot transact in the funds market to a sufficient degree to certainly avoid failing the reserve requirement test or running an overnight overdraft. Increased uncertainty generates an increased precautionary demand for reserves: days with higher payment flows are associated with increased demand for reserves and upward pressure on the funds rate. These predictable movements in the funds rate are not eliminated by arbitrage because penalties for overnight overdrafts limit banks' ability to smooth reserve shocks over time. Furfine (2000) estimated the model with a panel of depository institutions covering 1993 to 1997, and found that reserve uncertainty did increase significantly with payments volume. Simulating the model with the estimated parameter values showed that it could reproduce observed daily patterns in the level and volatility of the Federal funds rate.

In related work, Gaspar, Perez Quiros and Rodriguez Mendizabal (2008) investigated the relationships between the time-series and cross-sectional pattern of euro zone money market transactions and overnight rates. They studied the determinants of equilibrium in the market for daily funds using the EONIA panel database including information on transactions volume and lending rates for 64 banks from 1999 to 2002. Their results show that the time-series volatility and cross-section dispersion of rates, the volume of trade and the use of standing facilities all increase towards the end of the maintenance period. They argue that this is consistent with a decline in the elasticity of the supply of funds by banks during the reserve maintenance period. Thus the results support the argument of Perez Quiros and Rodriguez Mendizabal (2006) that the operational framework of monetary policy tends to induce a structural shortage of overnight funds towards the end of the reserve maintenance period.

Reserve requirements can affect the volatility of the overnight rate in two main ways (Wrase, 1998). First, banks use their accounts at the central bank for two distinct purposes: to hold reserves, and to settle payments with other banks. If banks minimise their reserves, they might become insufficient to settle payments, and create large swings in the overnight rate in response

to liquidity shocks. Second, low reserve holdings hamper the central bank's liquidity management, because banks' demand for reserves to settle payments is more variable than their demand to meet reserve requirements. Therefore, higher reserve holdings provide a liquidity buffer which facilitates banks' reserve management and the central bank's supply of reserves (Nautz and Schmidt, 2009). Fecht *et al.* (2008) studied the time patterns of euro zone banks' "reserve fulfilment ratios"¹⁷. They identified a general liquidity deficit at the beginning of the reserve maintenance period, when EONIA rates and hence the cost of liquidity tend to be higher. In contrast to other euro zone banks, German Landesbanks back-load the fulfilment of their reserve requirements over the reserve maintenance period and thereby benefit from the general pattern in the EONIA. Since the Landesbanks are the primary vehicles for collecting German savings, they typically enjoy greater liquidity and less uncertainty about reserves later in the maintenance period. These results underline the point that there is an interaction between reserve requirements and the structure of payments and settlement, so that the pattern of predictable variations in the overnight rate will tend to be different in different institutional settings.

Central bank intervention also affects the demand for reserves. Nautz (1998) uses an ARCH-M model to investigate German Bundesbank operations prior to EMU, and obtains two key results. First, when money market management is based on inflexible standing facilities for central bank credit, uncertainty about future refinancing has no impact on the overnight rate. Second, in a flexible repo-based money market management scheme, increased uncertainty about future refinancing reduces banks' demand for borrowed reserves and therefore reduces the interbank money market rate. Banks increase their reserves if refinancing is expected to be more expensive and if future refinancing conditions become more uncertain.

¹⁷ The reserve fulfilment ratio on any given day is defined as the ratio of a bank's cumulative actual reserves up to that day (from the beginning of the maintenance period) to its cumulative required reserves up to the same day.

Following Nautz (1998), several authors have investigated the impact of central bank intervention, for example, Bartolini, Bertola and Prati (2002). However, these papers focus on particular characteristics of the local money market. Bartolini and Prati (2006) present a unified framework that allows for rationed provision of liquidity as market rates depart from the central bank target and approach the marginal rates on borrowing or lending facilities. Their model captures the main cross-country differences along a key dimension of policy execution: a central bank's willingness to offset high-frequency liquidity shocks by injecting or draining liquidity into and from the market, at both intra-marginal and marginal liquidity-management facilities. Bartolini and Prati (2006) analyse the volatility of overnight rates for the seven largest industrial countries and a set of countries in the euro zone. They allow for the effects of reserve requirements and calendar time on the mean and conditional variance of interest rates, and for differences in the behaviour of overnight rates as between the last day of the maintenance period and other days. The overnight rate (i_t) is given by:

$$i_t = \mu_t + \sigma_t v_t$$

...(13)

$$\mu_t = i_{t-1} + \delta_{dt} + \delta_{ct} + \gamma \Delta_t$$

...(14)

$$\log(\sigma_t^2) = \lambda \log(\sigma_{t-1}^2) + (1 - \lambda L)(\xi_{dt} + \xi_{ct} + \omega \Sigma_t + \beta h_t^2 + \eta x_t^2) + k |v_{t-1}| + \theta v_{t-1}$$

...(15)

Here, μ_t is the conditional mean of i_t , v_t is a zero-mean, unit-variance i.i.d. error and σ_t is the conditional EGARCH volatility parameter. Central banks can control liquidity by combining

intra-marginal draining and injection of funds through repos, with marginal draining of funds at the floor (r_t^F) or injection at the ceiling (r_t^C), of the corridor for market rates around a key target rate (r_t^*). To study the volatility impact of these regimes, Bartolini and Prati (2006) control for the effects of official rates by including changes in r^F , r^* and r^C as determinants of the mean (14): $\Delta_t = \{(r_t^F - r_{t-1}^F), (r_t^* - r_{t-1}^*), (r_t^C - r_{t-1}^C)\}$. The conditional variance equation includes the position of the overnight rate in its target corridor (h_t), and that of the exchange rate (x_t) in its corridor. They include the usual calendar dummies in the mean (δ_{ct}) and variance (ξ_{ct}) equations as well as dummies for each day of the reserve period (δ_{dt} and ξ_{dt}). The empirical results provide broad support for earlier work such as Hamilton (1996) and Bartolini *et al.* (2002), Prati *et al.* (2003) and Gaspar *et al.* (2008). In all countries relying on reserve averaging, overnight rates on settlement days are more volatile than on other days; and higher volatility on settlement day tends to propagate to the immediately preceding days.

Nautz and Schmidt (2009) argue that these models¹⁸ fail to consider the effects of changes in the policy rate, including central bank communication policy, and the level of required reserves. They investigate how US monetary policy affects the dynamics and volatility of the Federal funds rate (i_t). The conditional mean equation is specified as an ECM:

$$\begin{aligned} \Delta i_t = & \theta' X_{1,t} + \sum_j \delta_j D_{j,t} + \alpha_1 D_{1,t} (i - i^*)_{t-1} + \alpha_2 (1 - D_{1,t}) (i - i^*)_{t-1} + \beta_1 (1 - D_{3,t}) (i_3 - i)_{t-1} \\ & + \beta_2 D_{3,t} (i_3 - i)_{t-1} + \varphi_1 \Delta i_t^* + \sum_{g=1}^5 \varphi_{2,g} \Delta i_{t-g}^* + \sum_{j=1}^5 \varphi_{3,j} \Delta i_{3,t-j} + \sigma_t \varepsilon_t \end{aligned} \quad \dots(17)$$

The funds rate adjusts to the policy spread between the funds rate and its target ($i - i^*$); and the term spread between three-month bills and the funds rate ($i_3 - i$). Dummy variables (D_i) are included to model changes in the monetary policy implementation regime and the usual calendar effects. The variance process is given by a standard EGARCH model which includes the volatility impact: of i^* ; the reserve ratio and the reserve requirement system; and the same policy

¹⁸ Especially, Bartolini and Prati (2006) and Perez Quiros and Rodriguez Mendizabal (2006).

and calendar dummies as in the ECM. The results show that greater transparency by the Fed did contribute to stabilizing the funds rate. The volatility of the funds rate varies inversely with the level of required reserves suggesting that reserve balances at the Fed do tend to facilitate the settlement of payments in the interbank market. This also suggests that the payment of interest on required reserves reduces the volatility of the Federal funds rate by broadening the reserve base.

Nautz and Offermanns (2007) investigate the impact of the ECB's policy rate and the term spread (the EONIA-euribor differential¹⁹) on euro zone EONIA dynamics from 1999 to 2004. Depending on the repo auction format, the policy rate is defined as the repo rate or the minimum bid rate set by the ECB in its weekly MRO tenders. End-of-maintenance-period effects in the EONIA are often related to banks' bidding behaviour in the MROs. Banks have an incentive to underbid when they expect a cut in interest rates within the maintenance period. Lack of reserves may then force banks to use the ECB's marginal lending facility increasing the EONIA towards the end of the maintenance period. Thus, interest rates may increase although underbidding has occurred, because banks expected interest rates to decrease. During the fixed rate tender period, expectations of a rate increase may lead banks to overbid (Välimäki, 2006). To reduce overbidding, the ECB regularly over-allotted reserves in the MROs; but then, contrary to banks' expectations, the EONIA fell at the end of the reserve period. The model is an ECM in which the EONIA adjusts to the policy spread (EONIA – the policy rate) and the EONIA-euribor (term) spread, with dummies to allow for different adjustment dynamics during the reserve period. It also allows for asymmetries in the adjustment process, including conditioning on the MRO auction format and for differences between within-reserve period adjustments and end-period adjustments.

¹⁹

Euribor is the three-month money market rate.

The results show that towards the end of the maintenance period, the influence of the policy rate on EONIA becomes weaker after the last MRO when reserve requirements have to be met without further access to central bank refinancing at the policy rate. For the term spread, the difference in adjustment for within-maintenance-period and end-of-period days is even more pronounced. From June 2000, the link between the EONIA and the ECB's policy rate strengthened when the policy spread increased. For both auction formats, within the reserve period, the adjustment of the EONIA is stronger when the policy spread is below average than when it is above average. However, the asymmetries in the adjustment process are independent of the MRO auction procedure. This is consistent with the findings of Ayuso and Repullo (2003). Likewise, there is no evidence of asymmetric adjustment of the EONIA at the end of the reserve period, irrespective of the auction procedure. Nautz and Offermanns (2007) suggest that the weak influence of the policy rate on the EONIA at the end of the reserve period may reflect the market's reaction to banks' over- and underbidding behaviour in the ECB's MROs.

The research discussed so far considers only the determinants of the conditional mean and volatility of the interbank rate. Finally, we note briefly the possible inter-linkages between the overnight and other rates. Sarno and Thornton (2003) estimated a non-linear VECM for the US Federal funds rate and the three-month Treasury bill rate and found that the adjustment of the overnight rate to the Treasury bill rate was asymmetric with negative deviations being corrected more quickly than positive deviations. The burden of adjustment was borne mainly by the Federal funds rate, underlining the need to consider the dynamics of other rates in the determination of the overnight rate. Kuo and Enders (2004) and Clarida, Sarno, Taylor and Valente (2006) suggest that asymmetric error-correction is also present in the Japanese and German term structure of interest rates. However, these papers do not consider the impact of the central bank's policy rate on the dynamics of the overnight rate.

The crisis of 2007-08 largely affected the financial markets of the western industrial countries. However, Japan experienced a financial crisis almost two decades earlier involving many similar features to that of 2007-08 namely: rapid credit expansion and an asset price bubble concentrated particularly in the housing market, followed by a collapse and a sharp rise in bad debts, especially within the banking sector (Okina, Shirakawa and Shiratsuka, 2000). The Bank of Japan responded with what is now described as “unconventional” monetary policy: aggressively buying assets to drive down short-term interest rates to zero followed in March 2001 by a programme of large-scale asset purchases, effectively a policy of QE.

There were two important consequences of the Bank of Japan’s policy. First, the uncollateralized overnight (interbank) call rate ceased to act as a policy indicator. With the call rate at zero, banks had little incentive to lend to one another in the uncollateralised overnight market when they could equally well hold risk-free reserves at the Bank of Japan at the same zero rate. Non-interest costs for lenders were higher in the interbank market than with the Bank of Japan. This was particularly stark in a setting in which the whole financial system was fragile following the crisis. Banks with fragile balance sheets held excess reserves as precautionary balances against a run on their deposits. Stronger banks had no wish to be contaminated by lending on an unsecured basis to riskier banks. The increased reluctance of banks to transact in the overnight market led to a marked decline in trading volumes, and the interest rate became less informative of market conditions. These issues were recognised by the Bank of Japan, as it changed its main operating target from the overnight call rate to the outstanding amount of banks’ reserves at the Bank of Japan (Shiratsuka, 2010). Second therefore, large-scale asset purchases did not lead directly to an increase in the quantity of broad money but to a large increase in excess reserves reflected in bank current accounts at the Bank of Japan (Ogawa, 2004; Shiratsuka, 2010).

It is therefore not entirely surprising that the 2007-08 financial crisis and the ensuing unconventional monetary policy measures such as QE have had effects which, in certain

important respects, parallel those that had previously transpired in Japan. We can divide the period into two: the crisis and its immediate aftermath, and implementation of large-scale QE.

Initially, as the crisis unfolded, central banks intervened to inject liquidity into the banking system on an unprecedented scale, and sharply reduced their policy rates towards zero (Cecchetti, 2010). However, there were important differences among the responses of central banks; for example the ECB intervened mainly through repo operations rather than the outright purchases undertaken by the Fed and the BoE (Joyce, Miles, Scott and Vayanos, 2012). In interbank markets of all maturities, interest rates increased sharply and became substantially more volatile; and trading volumes declined. In certain markets, lending dried up completely on some days, (Green 2011). Angelini, Nobili and Picillo (2011) find that aggregate risk was much the most important determinant of lending and interest rate spreads in European interbank markets with a maturity of at least one week (ie. excluding overnight loans). In fact, rate volatility and reluctance to lend were broadly comparable as between markets for secured and unsecured loans (Angelini *et. al.*, 2011).

In the overnight market, interest rates remained broadly anchored to central bank intervention rates, but volatility increased substantially. Even though overnight markets are for unsecured loans they did not encounter any complete freezes that were experienced in some markets for longer-term debt (Afonso, Kovner and Schoar, 2011). Indeed, volumes in the Federal funds market were not markedly affected by the financial crisis, notwithstanding the increased volatility in rates (Afonso, *et al.* 2011). However, Acharya and Merrouche (2013) document a fall in volume in overnight sterling markets in London; and Gabrielli (2009) identifies falls of broadly similar orders of magnitude during 2007-08 in the euro zone. These movements in aggregate trading volumes during the crisis mask a range of different influences. Researchers concur that the overwhelming consideration underlying the evolution of the overnight market and the demand for central bank reserves in the crisis era and the period immediately following was the demand by banks for liquidity, particularly for precautionary purposes. As in Japan

earlier, banks were reluctant to lend in the overnight market first because of doubts about the credit-worthiness of the borrower and second because of concerns on the part of the lending bank about its own capital and solvency. Several different factors may underpin this reluctance including incomplete contracting (Allen, Carletti and Gale, 2009) and asymmetric information (Cocco, Gomes and Martins, 2009).

An important consideration for policy-makers is that short-term liquidity is in part a public good²⁰. Different banks experience different costs of borrowing depending on their perceived individual characteristics. However, evidence from the crisis shows that if some banks were affected by liquidity problems, it caused a rise in borrowing costs for all banks. In times of crisis, the precautionary demand for liquidity tends to rise for all banks, thus reducing the supply of loans (Acharya and Merrouche, 2013). If this effect were strong we would expect to see a relationship between the time series of overnight rates (level and volatility) and their cross-sectional dispersion. Evidence from longer maturity interbank markets in the euro zone shows that the dispersion of rates among banks did rise during the crisis, especially for borrowers (Olmo, Iori and Kapar, 2014). Gaspar *et al.* (2008) found that there was a relationship between the cross-sectional dispersion of rates and their time series volatility within the euro zone in the period 2000-04 well before the financial crisis. It would be interesting to see if these relationships carry over to the crisis period.

The UK is an interesting laboratory to test the demand for liquidity as banks can choose their own target reserve level from maintenance period to maintenance period. The chosen reserve targets provide a more-or-less price-independent measure of demand. Acharya and Merrouche (2013) find evidence for distinct arbitrage and liquidity effects in the UK, but they could equally be called a supply and a public good effect, respectively. Arbitrage occurs in normal times when banks with excess liquidity release funds to lend to other banks; this tends to depress the

²⁰ Keynes was well aware of this issue: "... there is no such thing as liquidity of investment for the community as a whole." (Keynes, 1936, p. 155).

interbank rate implying a negative relationship between liquidity and the interbank rate (the supply effect). In the crisis, UK banks tended to hoard liquidity, especially on high transactions days, leading to a positive relation between liquidity and the overnight rate (the public good effect). Somewhat similar results were obtained for the euro zone by Gabrieli (2009): banks that made greater use of the overnight market during the financial crisis experienced generally higher borrowing costs. In addition, there were important differences between the unsecured and secured overnight market in the UK, with greater turbulence experienced in the market for loans which were secured (largely by UK government debt). Acharya and Merrouche (2013) attribute these differences to a selection effect; only the most highly-rated settlement banks were able to trade on an unsecured basis in the overnight market. Therefore the stresses to which weaker banks were subject were reflected primarily in the market for secured loans. In contrast, in the euro zone there were few identifiable differences between secured and unsecured interbank markets during the crisis, at least at longer maturities than overnight (Angelini *et. al.*, 2011).

The second phase was the aftermath of the crisis. Over this period, central bank policies have had two key effects on the overnight market and the demand for reserves that are broadly similar to those of the Bank of Japan over a decade earlier. First, in the overnight market, interest rates have fallen to the bottom of the corridor used by central banks, and the volatility of the rate has generally declined from the crisis period. Second, volumes traded in overnight markets have tended to decline sharply (Jackson and Sim, 2013). Research on these outcomes has concentrated on the special features of QE in generating a huge increase in bank reserves (Afonso and Lagos, 2015). However, the earlier contribution of Furfine (2000) demonstrated the importance of the dual functions of bank reserves that we drew attention to in section 2, namely that they are used for monetary management and to finance the payments mechanism. Furfine verified that banks with higher excess reserves are better able to manage payments shocks with less recourse to the interbank market, implying reduced interbank transactions, and a lower and

less volatile interbank rate. It is therefore not really surprising that the huge increase in excess reserves has had these same effects for the banking system as a whole.

Second, there has been a massive increase in excess reserves held at central banks with little significant impact on the growth of broad money in any of the countries in which QE has been implemented (Goodhart and Ashworth, 2012). The reasons for these outcomes are still being worked out. See the recent theoretical contributions of Afonso and Lagos (2015) in the federal funds market and Hauck and Neyer (2014) on the euro zone. However, it seems clear that the increase in reserves does reflect in part an increase in precautionary demand and corresponding reluctance to engage in unsecured overnight borrowing or lending

These developments raise a more general question about the future of the overnight market, at least as long as unconventional monetary policy is in place (Borio and Disyatat, 2010). Once the main policy interest rate reached its zero bound with a commitment that it would remain there, central banks were no longer employing an interest rate as their main operational target. Instead they were targeting bank reserves through QE. In its 2001 initiation of QE, the Bank of Japan acknowledged this explicitly, switching from the call money rate to bank reserves as the key operating target. Western central banks have generally continued to treat the interest rate as their ostensible operating target, notwithstanding that it appears nugatory. If trading in overnight markets is thin and banks have excess reserves on the scale that has followed from QE, the overnight rate may be of little value as policy indicator. This underlines the need for central banks to have clear exit strategies from QE (Borio and Disyatat, 2010).

Available estimates suggest that there is a very high cross-elasticity of demand for central bank reserves with respect to the overnight rate. Ogawa (2004) estimated that a 5 basis points increase in the Japanese overnight call rate could have been sufficient to reduce excess reserves by up to 40% following the Japanese crisis and its own QE which began in 2001. Marquez, Morse and Schlusche (2013) estimate that a \$1tr (or about 2/3) cut in excess reserves would raise the

Federal funds rate by only about 25 basis points following the Fed's QE programme. The estimates of Marquez *et. al.* are based on a simultaneous model of reserve demand and interest rate determination whereas Ogawa's model is a single-equation (reduced form) demand function for reserves. However, Ogawa's study contains an important element not considered by Marquez *et. al.* namely, an allowance for bad loans. We would expect the cross-elasticity of reserve demand to be very sensitive to the underlying soundness of individual banks and to the system as a whole. Ogawa estimated that if the 5 basis point rise in the call rate is accompanied by a 50% cut in banks' non-performing loans, excess reserves would decline by over 50%. These estimates do not however, fully address the more important issue of how the excess reserves are to be extinguished, whether by a decrease in reserve supply or an increase in broad money. Evidently it is the former that is desired.

8 Concluding Remarks

The overnight interbank market is closely linked with the market for bank reserves, providing "next-to-last-resort" unsecured borrowing facilities for commercial banks. The literature suggests that this creates the need for networks involving long-term banking relationships. Interbank networks tend to develop a "core-periphery" structure based on these relationships. A sparse network of this kind can be vulnerable to contagion, but this depends in part on the characteristics and position of each bank in the network. Under certain conditions sparse networks can be less vulnerable to contagion. There is also evidence that networking promotes the monitoring of borrowers by lenders, creating some degree of market discipline. The vulnerability to contagion of any network changes over time and more needs to be understood about how to recognise when vulnerability increases to dangerous levels.

Theoretical and empirical research on the determinants of the overnight interest rate suggest that it is influenced by a range of factors, including daily payment flows and central bank and operations, especially interest rates, reserve requirements and open market policies. The

substitutability between overnight loans and bank reserves depends on the relative costs of transacting in these markets, including interest and non-interest costs such as collateralisation. Aggregate liquidity shocks affect the equilibrium rate unless the central bank increases the supply of bank reserves. Shocks that redistribute liquidity among banks can also affect the rate through several different channels. A redistributive shock alters the inter-bank dispersion of borrowing and lending in the market and therefore the cross-sectional distribution of rates paid and charged. Temporary payments shocks may be managed through market mechanisms, but if the shock is permanent it may affect the perception or reality of the soundness of individual banks. Because of the risks of contagion, the market for overnight loans contains elements of a public good: an improvement or deterioration in the quality of a few banks' balance sheets may affect the rates charged on all loans, not just those to the affected banks.

Bank reserves (and therefore overnight loans) are not perfect inter-temporal substitutes across maintenance periods; and there is also strong evidence that they are not perfect substitutes within a single maintenance period, partly because of transactions costs and other frictions and also because of asymmetries inherent in reserve maintenance systems. There is abundant evidence of predictable movements in the conditional mean and variance of the overnight rate, both within the day and between days in any single maintenance period. The time-paths of mean and variance are system-dependent and vary across countries; but they are broadly related to the institutional arrangements in each country particularly for reserve requirements and central bank intervention. However, there is some evidence of efficiency in respect of central bank policies in the US and euro zone where expected policy announcements have been found to have a greater impact on mean and variance than the announcements themselves. This would suggest that these central banks do communicate effectively with the market. Empirical modelling of the overnight rate tends to confirm that the conditional mean and variance are determined by a complex set of factors, including other short-term interest rates, central bank rates, the exchange rate (where the central bank has an exchange rate target) and relevant quantities, such as the amount and terms

of central bank operations, and daily fluctuations in payment flows through the settlement system. Measures of the cross-sectional dispersion in daily transactions also help explain the time series pattern of the average rate.

The 2007-08 financial crisis has wrought substantial changes in central bank policy-making and intervention tools and in the role of the overnight market, at least in the major industrial countries principally affected by the crisis. Trading in the major overnight markets is less active as banks prefer to lend to the central bank rather than to one another, and the overnight rate has lost much of its policy importance in the major industrial countries. There have been some substantial theoretical contributions to understanding overnight markets but there has been less empirical work. Much more remains to be done in understanding if the overnight market has a new role to play or if it will eventually revert fully to its traditional functions.

The main omission from this survey concerns overnight markets in emerging economies. There are many such markets (BIS, 1999) but most research on emerging economies has been concerned with interbank markets in general, rather than with the overnight market in particular, and with a focus on networking and contagion. There are relatively few research results on the determinants of overnight rates in emerging markets and their relation to monetary policy²¹. Few emerging markets experienced the same financial trauma of 2007-08 as the industrial west, and their overnight markets have mostly not gone into reverse. Research on the main western markets shows that the behaviour of overnight rates is linked inextricably to distinctive institutional conditions in each market. These considerations suggest that an important priority is to continue to extend research on overnight markets to a wider range of countries to better understand the variety of experience and the lessons to be learnt for monetary policy and the banking system.

²¹ An important issue is that relatively few countries dispose of readily available separate data on transactions in the overnight markets. Even for the US, Furfine's (1999) seminal contribution was based on estimated transactions in federal funds rather than the actuals. We thank an anonymous referee for this point.

Overall, the main contributions of this paper are five. First, we provide a selective survey of the literature on overnight interbank markets, concentrating on the major industrial countries, at the opportune time when these markets are attracting increasing interest from researchers, policy makers, and practitioners. Second, we outline the typical structure of overnight markets and their relationship to bank reserves; we explain the potential conflicts faced by central banks between the provision of reserves for payments purposes and reserves required for meeting monetary policy objectives. Third, we identify critical issues in networking in overnight markets. The literature does not yet provide clear answers as to whether complete or incomplete networks are more robust in limiting contagion from the failure of individual banks; this is a promising research area, calling for innovative research approaches. Fourth, we explain the theory of and document key empirical results concerning the determination of the overnight interbank rate. The overnight rate typically displays predictable daily movements within and between bank reserve maintenance periods; these regularities vary among countries and can generally be traced to the institutional structure of reserve management in a country. Fifth, we identify important changes in the structure and functioning of overnight markets following the 2007-08 financial crisis. Markets have tended to become less liquid following the crisis and there remain important issues concerning future market developments as central banks seek to move normalise monetary policy from their post-crisis use of unorthodox policies such as large-scale asset purchases.

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Overnight Interbank Markets and the Determination of the Interbank Rate: A Selective Survey

Research Highlights

- We provide a selective survey of the literature on overnight interbank markets concentrating on the major industrial countries.
- We outline the typical structure of overnight markets and their relationship to bank reserves; we explain the potential conflicts faced by central banks between the provision of reserves for payments purposes and reserves required for meeting monetary policy objectives.
- We identify critical issues in networking in overnight markets. The literature does not yet provide clear answers as to whether complete or incomplete networks are more robust in limiting contagion from the failure of individual banks.
- We explain the theory of and document key empirical results concerning the determination of the overnight interbank rate. The overnight rate typically displays predictable daily movements within and between bank reserve maintenance periods; these regularities vary among countries and can generally be traced to the institutional structure of reserve management in a country.
- We identify important changes in the structure and functioning of overnight markets following the 2007-08 financial crisis. Markets have tended to become less liquid following the crisis and there remain important issues concerning future market developments as central banks seek to move normalise monetary policy from their post-crisis use of unorthodox policies such as large-scale asset purchases.

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